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## **BREAKTHROUGHS IN LOW-PROFILE LEAKY-WAVE HPM ANTENNAS**

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**18 Sept 2014**

**Data Item: A001 - Progress, Status, & Management Quarterly Report #4**

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 18-09-2014		2. REPORT TYPE Quarterly		3. DATES COVERED (From - To) 19 Jun 2014 - 18 Sep 2014	
4. TITLE AND SUBTITLE Breakthroughs in Low-Profile Leaky-Wave HPM Antennas Progress, Status, & Management Report (Quarterly Report #4)				5a. CONTRACT NUMBER N00014-13-C-0352	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Koslover, Robert, A.				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Scientific Applications & Research Associates, Inc. 6300 Gateway Drive Cypress, CA 90630-4844				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 North Randolph Street Suite 1425 Arlington, VA 22203-1995				10. SPONSOR/MONITOR'S ACRONYM(S) Code 30	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution Statement A. Approved for public release; distribution is unlimited. Other requests for this document shall be referred to the Program Officer listed in the contract.					
13. SUPPLEMENTARY NOTES ..					
14. ABSTRACT This report describes progress during the 4th quarter of this program and summarizes the current status of the research. Our primary technical activities this period consisted of (1) identifying a significant generalization of the leaky-wave apertures under investigation, promising substantially-improved conformability and application to curved, interrupted, and/or irregular platform surfaces; and (2) a way to reduce antenna depth in some circumstances, potentially easing packaging and system integration. These latest research paths may expand the applicability of this technology beyond what was originally anticipated.					
15. SUBJECT TERMS Leaky-wave Antennas. High Power Microwaves (HPM) Antennas. Low-profile Conformal Antennas.					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  SAR	18. NUMBER OF PAGES  —	19a. NAME OF RESPONSIBLE PERSON (Monitor) Lee Mastroianni
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (incl. area code) (703) 696-3073

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# 1. INTRODUCTION

This is SARA's 4<sup>th</sup> Quarterly Report for "Breakthroughs in Low-profile Leaky-Wave HPM Antennas," a 37-month Basic Research effort sponsored by the US Office of Naval Research (ONR). This work includes fundamental theoretical analyses, numerical modeling, and related basic research. Objectives include to discover, identify, investigate, characterize, quantify, and document the performance, behavior, and design of innovative High Power Microwave (HPM, GW-class) antennas of the *forward-traveling, fast-wave, leaky-wave* class. The variety of HPM antennas within this class has grown in the nearly ten years since our invention of the FAWSEA (December, 2004). Table 1 below identifies the names and acronyms we have assigned so far, along with some identifying features. The reader may notice *two new names* (BAWSEA, GAWSEA), which are discussed later in this report.

**Table 1. Types of low-profile, forward-traveling, fast-wave, leaky-wave, HPM antennas**

Acronym	Full Name	Identifying Geometry / Feature(s)
FAWSEA	Flat Aperture Waveguide Sidewall-Emitting Antenna	Flat linear aperture, parallel straight channels.
CAWSEA	Curved Aperture Waveguide Sidewall-Emitting Antenna	Aperture curved in E-plane. Curvature may be compensated via delays introduced at feeds.
AAWSEA	Arched Aperture Waveguide Sidewall-Emitting Antenna	Aperture curved in H-plane. Curvature may be compensated via varying $\beta$ along guides.
RAWSEA	Rotated Aperture Waveguide Sidewall-Emitting Antenna	The leaky channels are tilted relative to the aperture, notably reducing the antenna's depth.
PAWSEA	Pinched Aperture Waveguide Sidewall-Emitting Antenna	Double- or triple-curved aperture customized to conform to part or all of an ogive (nose cone).
BAWSEA*	Bent Aperture Waveguide Sidewall-Emitting Antenna	Aperture curved in the aperture plane. Curvature compensated via varying $\beta$ along guides.
GAWSEA*	Generalized Aperture Waveguide Sidewall-Emitting Antenna	An aperture with multiple-curvatures or complex topology. Curvature and topology compensated via delays at feeds, varying $\beta$ along guides, imbalanced power division among channels, etc.

\*New developments, this quarter.

## 1.1. Overview of Previous Activities (1<sup>st</sup> thru 3<sup>rd</sup> Quarter)

During the *first* quarter, we prepared and established useful equations and algorithms for predicting reflections and transmission of incident TE waves from parallel-wire grills, dielectric windows, and combinations of wire grills with dielectric windows, in problems reducible to purely H-plane (2D) representations. We then applied this theory to guide the design of high-gain configurations (again, limited to 2D, H-plane representations) for linear, forward traveling-wave, leaky-wave antennas. The theory built upon equivalent circuit methods and wave matrix theory, which provided useful formalisms upon which we continue to build.

During the *second* quarter, we pursued initial extensions of the previous work into three dimensions, in order to include phenomena with E-plane dependencies. We succeeded in adding into the wave-matrix formalism the reflection/transmission properties associated with the transition to free space from a *finite-width* leaky-wave channel, including the edge-tapering essential to HPM applications. These geometric aspects do not arise in analyses confined to the H-plane alone. Our 3D analyses were somewhat more

reliant on numerical models than in the 2D analyses, due to the greater complexity of identifying and/or building practical analytic approaches capable of addressing true 3D geometries of interest.

During the *third* quarter, we explored channel-to-channel coupling (aka, mutual coupling) which (as we have noted earlier) is an important design concern, since it can impact antenna performance significantly in terms of gain, peak power-handling, and impedance matching. Our approach leveraged mostly numerical methods, along with some intuitive arguments, as we explored designs exhibiting different degrees of mutual coupling between adjacent channels. As past and current antenna literature attest, mutual coupling analyses are non-trivial; suffice to say, there is still much work to be done in this area.

For more information, we encourage the reader to refer our earlier *Quarterly Report #1*, *#2*, and *#3*.

## 1.2. Overview of Recent Activities (4<sup>th</sup> Quarter)

During the first part of the *fourth* quarter, we continued to study and employ wave-matrix based methods, but with less success than before in combining the analyses with numerical models, and in subsequently using those combinations to improve/optimize designs. This appears to be due to the increasing challenge of attempting to represent various 3D and curved geometries with *closely-spaced* (and thus more locally-interacting) parts as equivalent to isolated, subsequently linked (via the matrix chain method) and using local (i.e., with slowly-varying amplitudes and phases along interfaces) superposition of forward and reverse plane-waves. The formalism itself is still valid, but it evidently offers reduced practical rewards when and where establishing a well-defined sequence of interfaces – each interface with its own identifiable reflection & transmission coefficients or equivalent circuits – becomes particularly difficult.

While still pondering the best way to advance the analyses tasks, we have increased our pursuit of new and improved antenna configurations. We are pleased to report here that this effort has led to the identification of *new aperture geometries* of potentially-significant and practical value. In particular, we present in this report the first discussions of the new “BAWSEA” and “GAWSEA” configurations. Finally, later in this report, we describe a way to potentially reduce antenna depths (in some cases).

Section 3 describes the technical work mentioned above in more detail.

## 2. STATUS OF THE PLAN/SCHEDULE AND FUNDING

Figure 1 (next page) maps out the updated program plan, for quick reference. As of the time of this report, at the analysis level, we are now transitioning our efforts away from Tasks 2.1 and (but less so) Task 2.2, toward attention to the newer (additionally-curved apertures plus RAWSEA) variants, and have initiated analyses of the very newest concepts (Task 2.5, Tasks 4.1-2) much earlier-than-anticipated, due to early identification this period of intriguing new BAWSEA and GAWSEA concepts. We will, of course, soon have to renew/boost efforts on the design recommendation/optimization tasks {3.1 – 3.5}.

The subject contract was awarded on 9/18/2013 and has an end date of 10/17/2016. The total contract value is \$868,350, with current (per P00003 signed on 4/24/2014) allotted funding of \$406,530. According to SARA’s accounting system as of Sept. 12, 2014, expenses (including fee) have totaled \$268,511, thus leaving \$138,019 available. (If one simply compares the calendar and spending on this project, we have consumed ~32% of the calendar and ~31% of the contract value.)

There are no technical, schedule, or funding-related program problems/concerns to report at this time.

## Plan of Action and Milestones (POA&M) (updated Sept 2014)

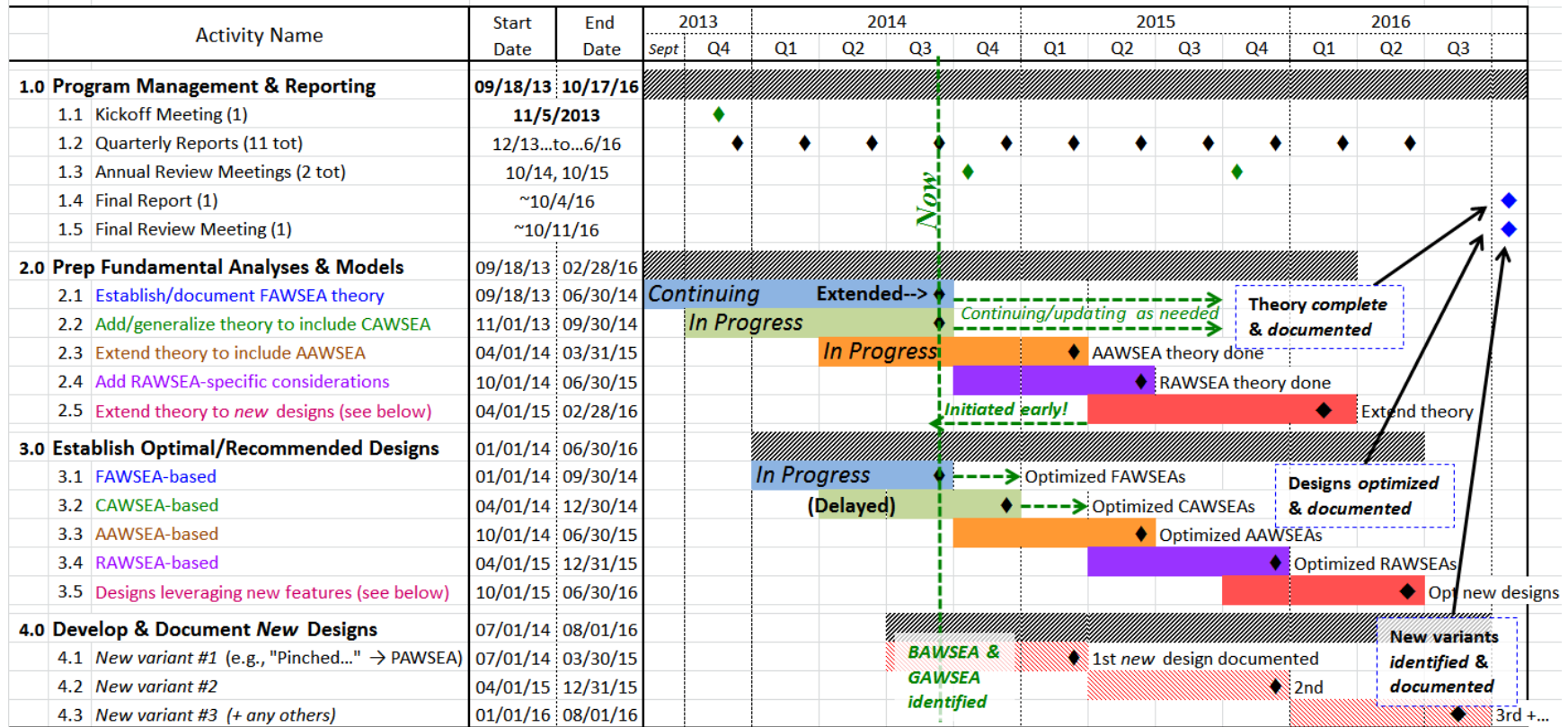
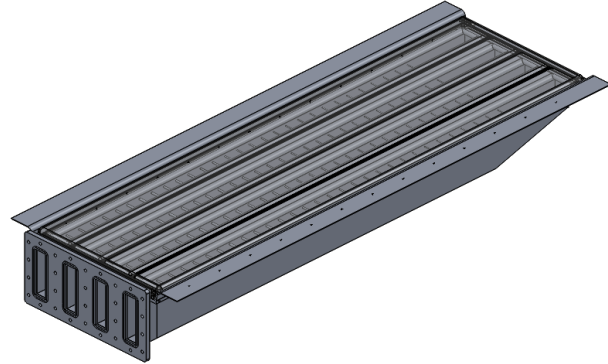


Figure 1. Updated Program Plan

### 3. RESEARCH PERFORMED THIS PERIOD

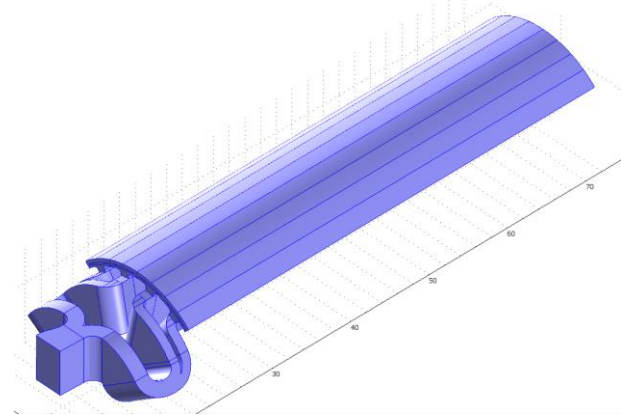
#### 3.1. Introducing the Bent Aperture Waveguide Sidewall-Emitting Antenna (BAWSEA)

**Background:** In most HPM-based DEW applications, it is desirable for the antenna aperture to deliver a single, high-gain, beam. In the FAWSEA, this is done via phase-matching a controlled leak-rate, forward-traveling, fast-wave (i.e.,  $v_\phi > c$ ) within one or more parallel waveguides (aka, channels), with a radiated plane wave that exits the overall aperture at a well-defined angle. Since the FAWSEA aperture is flat and the waveguides are straight (e.g., Figure 2), the ideal distribution of  $v_\phi$  is simply a constant, independent of position or channel.



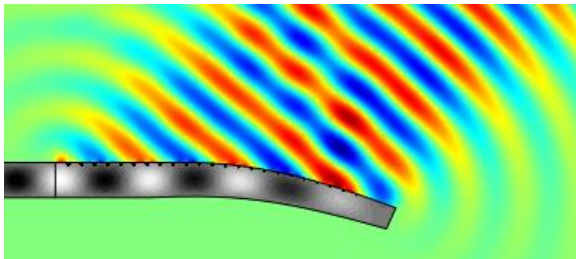
**Figure 2. Example FAWSEA (not incl. window)**

The CAWSEA is similar, but the channels are splayed outward such that the aperture is curved in the E-plane. One can re-establish phase-matching to a radiated plane wave by introducing differing phase delays at the feed, such as in Figure 3. But the ideal distribution of  $v_\phi$  throughout the leaky waveguides in the antenna is still a constant, independent of position or channel.



**Figure 3. Example 4-channel CAWSEA with a phase-delaying structure (lower left) to compensate for the aperture curvature.**

In contrast, the AAWSEA introduces curvature in the H-plane, which requires us to modify  $v_\phi$  vs. position along the channels, to maintain a clean match to a radiated plane wave. The required variation in  $v_\phi$  is achieved by varying the depth of the channels, such as shown (side view) in the numerical model snapshot in Figure 4.



**Figure 4. Model of an AAWSEA (side view) with a tapered waveguide depth to compensate for the aperture curvature.**

and tilt, we must gradually decrease the wavenumber (increase  $v_\phi$ ) in each channel vs angle as the waves go around the bend. Figure 6 shows how to set the waveguide depths (actually *effective* depths, when adding leaky interfaces later) to deliver this required phasing. Figure 7 then shows a couple of initial numerical model geometries that we set up to test the efficacy of this BAWSEA-phasing plan.

**Introducing the BAWSEA:** Consider curving the aperture *around the third axis* (i.e., the normal to the aperture), which is the same as curvature within the aperture plane (if one starts with a flat aperture). This kind of “bent” aperture embodies the BAWSEA concept. To be most useful, and just as with the CAWSEA and AAWSEA, we must deliver field conditions to the aperture that, *despite the curvature*, match a radiated plane wave at a well-defined angle. Consider a simple bend, such as shown in Figure 5.

We see that to maintain the radiated-wave direction



Consider channels bent in an arc.  
To get a high-gain beam, we require:

$$\beta_n r_n d\theta_n = \beta_T dy$$

for all  $n$ , where  $\beta_n$  is the wavenumber along the  $n^{\text{th}}$  curve, and  $\beta_T$  is the desired traveling wavenumber along  $y$ .

Since  $y = r_n \sin \theta_n$ , we promptly obtain

$$\beta_n = \beta_T \cos \theta_n$$

as the required behavior of the wavenumber in the  $n^{\text{th}}$  channel.

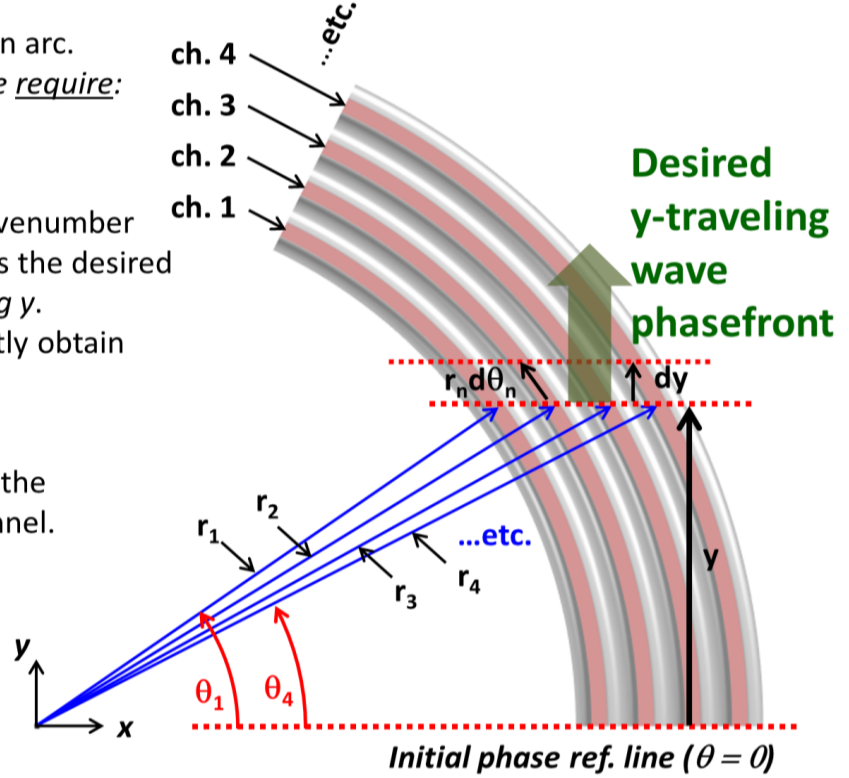


Figure 5. Derivation of BAWSEA channel-phasing to yield a single high-gain beam.

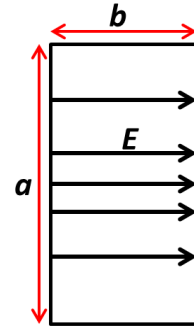
The wavenumber  $\beta$  for propagation of the fundamental mode in a rectangular cross-section evacuated waveguide of dimensions (a,b) is:

$$\beta = \frac{2\pi}{c} \sqrt{f^2 - \left( \frac{c}{2a_{\text{eff}}} \right)^2}$$

(For a *leaky-sidewall* waveguide, we have replaced  $a$  with  $a_{\text{eff}}$ , since the leakage modifies that effective dimension slightly.)

Solving for  $a_{\text{eff}}$  in terms of  $\beta$ , we obtain:

$$a_{\text{eff}} = \frac{\pi}{\sqrt{\left( \frac{2\pi f}{c} \right)^2 - \beta^2}} = \frac{\pi}{\sqrt{k_0^2 - \beta^2}} \quad \text{where } k_0 \text{ is the free-space wavenumber.}$$



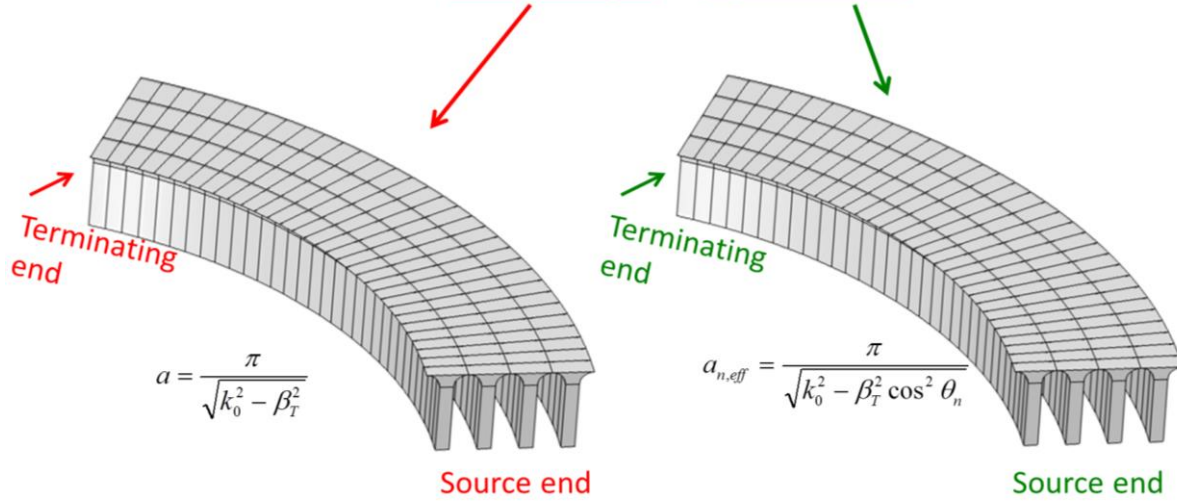
From before, if we now apply this rule to the  $n^{\text{th}}$  channel, we obtain:

$$a_{n,\text{eff}} = \frac{\pi}{\sqrt{k_0^2 - \beta_n^2}} \rightarrow \boxed{a_{n,\text{eff}} = \frac{\pi}{\sqrt{k_0^2 - \beta_T^2 \cos^2 \theta_n}}}$$

This equation tells us **how to set the (effective) depth** of each channel in the BAWSEA **as a function of angle**, if the channel is to be bent along a circular arc.

Figure 6. Determination of the required BAWSEA channel effective depths.

Let's compare 3D models with constant depth vs adjusted depth BAWSEA channels.

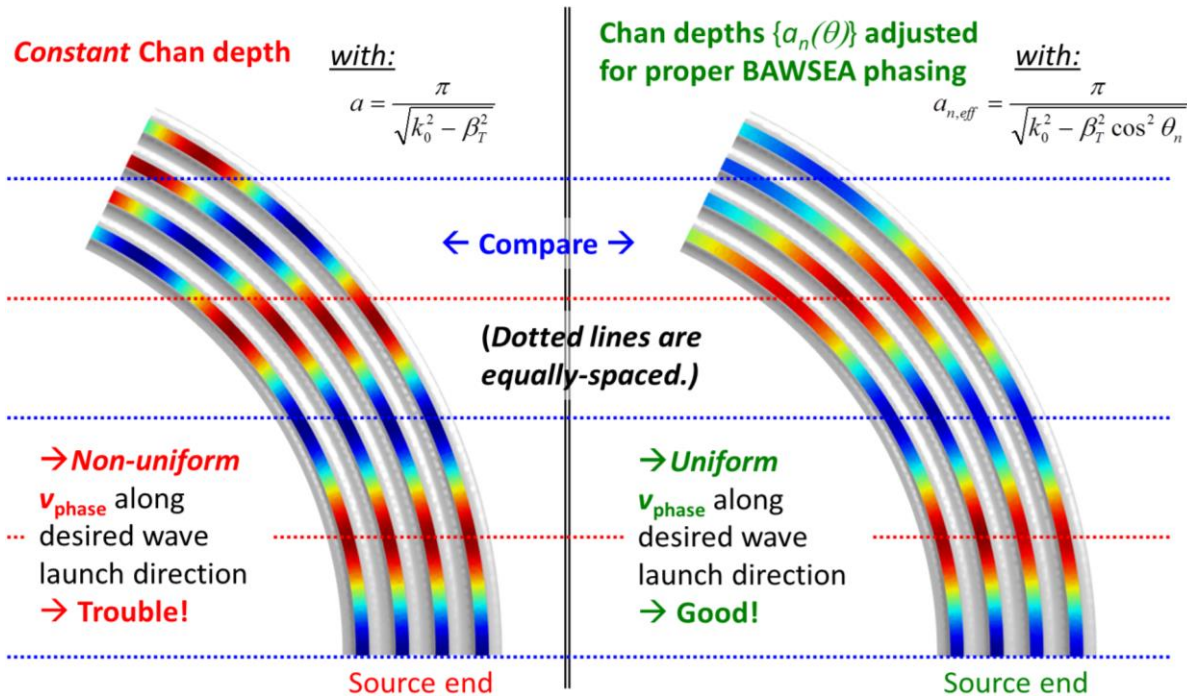


*{Note: It is easiest to see the geometric difference if you compare the structures near their terminating ends.}*

**Figure 7. Geometry of 3D models with constant (left) and adjusted (right) depths.**

Figure 8 shows the wave phasing that results from the fundamental-mode waves propagating around the bends in the waveguides in the models from Figure 7. It is clear, and not surprising, that making proper adjustments to the depths of the guides is essential to compensate for bends through significant angles.

Computed examples below are with non-leaky channels (for computational simplicity)  
(Plots of fields are slices in mid-channels. BAWSEA set to fit a nominal 30° rel-to-norm output beam)

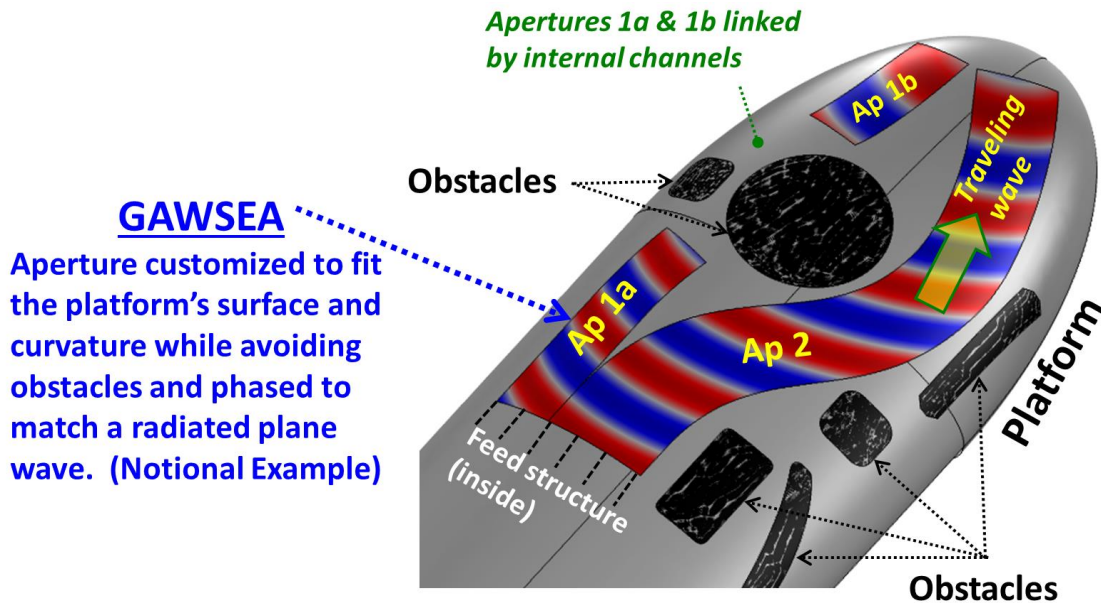


**Figure 8. Phasing that results from constant (left) vs adjusted (right) depth channels.**

As with an AAWSEA or CAWSEA, there are limitations to how much curvature can be tolerated and compensated for in a BAWSEA. As with the AAWSEA, it should go without saying that one should not try to curve the aperture so much that the required compensation would lead to cut-off or a reversal of the wave propagation direction in any of the leaky channels. Likewise, one should probably not curve the guides so much that the dominant field components present become excessively misaligned with the polarization desired in the radiated wave. Our prior work<sup>1</sup> strongly suggests that aperture distributions formed from moderately-misaligned channel-to-channel fields can still yield quite respectable performance in terms of VSWR, bandwidth, power-handling, and gain. The same must apply to (at least) modest amounts of BAWSEA curvature; we will do additional analyses to clarify and quantify the impacts.

### 3.2. The Generalized Aperture Waveguide Sidewall-Emitting Antenna (GAWSEA)

With the addition of the BAWSEA mentioned above, it becomes increasingly clear that, within certain constraints, it must be possible to define an even broader family of forward-traveling, fast-wave, leaky-wave, HPM-capable apertures, which in turn should enable effective customization of HPM DEWs to even rather complex surfaces. Even greater design flexibility would arise from allowing waveguide connections between separated leaky-wave structures to support multiple apertures, introducing delays if/as needed, at locations other than just the initial feeding inputs, and to resynchronize phases at the midpoints as might become necessary. One could introduce variations in propagation (wavenumber) along the paths to compensate for modest changes in leaky-waveguide direction, on a per channel basis if needed, once again to better fit to the required plane-wave boundary-matching conditions. Multiple channels comprising such an antenna need not necessarily be always adjacent to one another. One could define an overall aperture such that it split apart and then smoothly surrounded the sides of an obstacle or opening on a platform (e.g., a window, landing gear, fuel-port, vent, etc.) that would otherwise have prohibited the placement of the aperture there. It is from this kind of perspective that we are now investigating options for “generalized” aperture waveguide sidewall-emitting antennas (GAWSEAs). A notional representation exhibiting some of the features listed above is provided in Figure 9.



**Figure 9. This Generalized Aperture Waveguide Sidewall-Emitting Antenna (GAWSEA) features multiple channels & curvatures and a distribution of leaky-wave apertures to yield an overall aperture, customized for maximizing power delivered against a target.**

<sup>1</sup>This includes investigating beam steering from multi-channel FAWSEAs with significant channel-to-channel phase differences, as well as analyses of CAWSEAs with phase-compensating feeds.



Interestingly, one of the major constraints of a BAWSEA or AAWSEA – that channel curvatures cannot extend so far that the waveguides would need to reach or pass through cutoff to compensate – can potentially be *relaxed*, if the trouble-making sections are replaced by non-leaky-wave connections. Thus, the distribution of what may appear (at the platform surface) to be disjoint apertures, as envisioned in the GAWSEA concept, may prove to be an especially powerful feature, despite the additional engineering associated with the increased number of aperture boundaries (more feeds and terminations) that it brings.

If the GAWSEA notion seems too radical, remember that although aperture geometry is an *important* consideration in the design of any aperture-type antenna, there is *no fundamental theoretical requirement* that physical apertures, whether used individually or as arrays, exhibit simple, symmetric, contiguous, or attractive cross-sectional shapes, nor that arrays be uniformly-spaced. This is true despite the fact that the majority of (but not all) aperture antennas (horns, reflectors, lenses, etc.) invented, designed, engineered, and/or built during the last 100 years have exhibited rectangular, circular, elliptical, or similarly-appealing cross-sections, and most aperture arrays (but not all) are uniform. Such choices stem from direct or indirect application of established design principles, can be specified using well-documented rules and simplifications, often provide elegant amenability to both analytics and aesthetics, and have symmetries and uniformities that ease fabrication and keep manufacturing costs reasonable. And yet, most of the time, those antenna apertures *do not actually need to be those particular shapes<sup>2</sup> to do their jobs*. HPM antennas (and other antennas) may not be made of modeling clay, but their designs can nowadays be shaped, analyzed, reshaped, and reanalyzed at will, with the aid of powerful computers and modern 3D full-wave RF modeling tools. Practical GAWSEA design definitely requires using those kinds of tools.

### 3.3. Shallower-depth antennas.

In contrast to the other antennas listed after the FAWSEA in Table 1, the key innovation embodied by the RAWSEA (Figure 10) is its shallower depth, achieved due to rotation of the leaky-wave channels. However, since fundamental mode waveguides can almost always be gently curved in both E and H planes, it should be possible to combine RAWSEA-type leaky-wave channels in designs that also incorporate curved-apertures, albeit subject to some mechanical limitations arising from having to keep the waveguide channels from overlapping.

An alternative is to *replace the rectangular cross-section waveguide channels with double-ridged waveguides* (see Figure 11). There are two main prices to pay for doing that: (1) reduced peak-power handling, due to field enhancements and reduced waveguide cross-sectional area, and (2) greater complexity (and thus cost) in fabrication. (In principle, double-ridged guides could also be employed in a RAWSEA-type

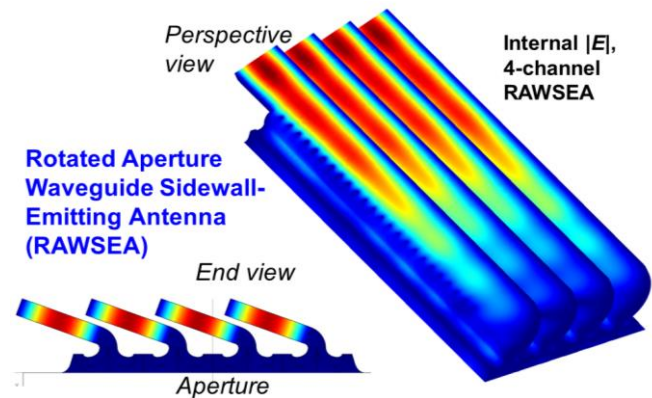


Figure 10. A RAWSEA (from a 3D model).

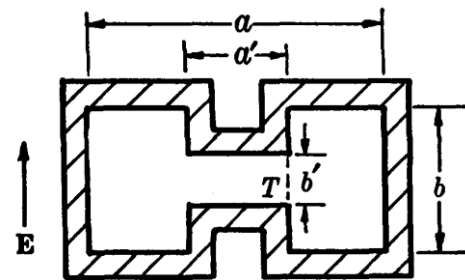


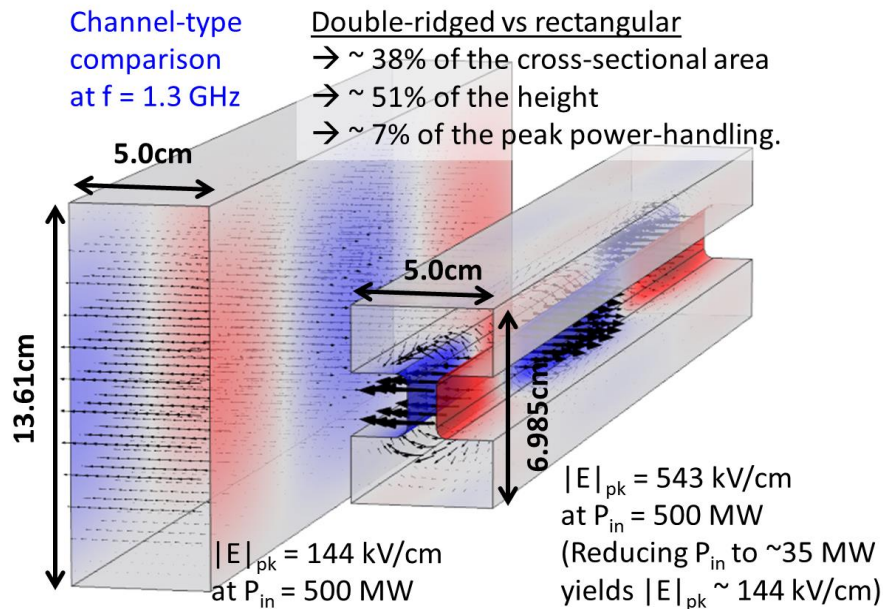
Figure 11. A Double-ridged<sup>3</sup> Waveguide

<sup>2</sup> When aperture shape is critical, it is most often due to relative phasing requirements. If there exists sufficient flexibility to control phase in the design, geometric constraints are more relaxed. The CAWSEA, AAWSEA and BAWSEA provide examples of this flexibility, enabling conformance to curved surfaces. The GAWSEA combines and generalizes all those tools to achieve even greater design flexibility.

<sup>3</sup> Figure borrowed from Marcuvitz, N., *Waveguide Handbook*, McGraw-Hill, NY, 1951.

geometry, although the resulting benefit would be less dramatic than in other arrangements due to the rotated orientations of the guides.) Interestingly, even if one cannot tolerate any reduction in peak-power handling, there can still be a role for double-ridged waveguide, if the ridges are introduced gradually as one transitions from the feeds-end to the terminations-end of the antenna. This is because the power being carried in the channels decreases (and does so approximately linearly, in a good design) from the feed to the termination. Introducing a smooth transition/tapering from rectangular to double-ridged waveguides toward the termination end of the antenna allows the latter region to be made with a shallower depth. The improvement may be enough to make the difference in some cases (perhaps where a PAWSEA configuration is required, for example).

Figure 12 shows two waveguides on the same scale, rectangular (left) and double-ridged (right), exhibiting the same cutoff frequencies (and so the same propagation constants) and carrying the same power. Note the differences in physical size and peak values of the interior electric fields. Although the peak power-handling of the double-ridged waveguide is clearly inferior, it is also much smaller, which could make the difference in some tight-packaging applications.



**Figure 12. Comparison of rectangular vs. double-ridged waveguide channels.**

Interestingly, the surface current distributions and tangential fields in the 5cm-wide walls in the above waveguide examples are ~identical, so at first glance, it might seem that, aside from the reduction in peak power-handling, the double-ridged waveguide on the right in Figure 12 could be used as a “drop-in” replacement channel, for a FAWSEA antenna using the example waveguide on the left in Figure 12, all without needing to redesign the wire-grill, tapered region of the aperture, aperture window, etc.

Unfortunately, this is *not* the case, as we have observed via models not further described here. Rather, local interactions arising between the finitely-spaced wire-grill and the relatively-nearby ridges disturb the field distribution in the guide significantly, negatively impacting the performance of the antenna. Of course, it is still *possible* to design leaky-wave wire grills, windows, etc. for antennas with double-ridged waveguide channels. But the design equations/techniques (such as embodied in the Matlab functions and scripts in our previous reports) will need to be adjusted. Depending on the complexity of this task (and the level of interest expressed by ONR in advancing shallower, but reduced  $P_{pk}$  antennas) we may or may not prioritize that research path in the coming months.

#### **4. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS**

We are pleased to report that work performed during this 4<sup>th</sup> quarter of the R&D program has expanded the family of potential HPM antenna options to consider, especially in those cases where platform-integration is the most challenging factor.

We look forward to further extending the theory, documenting representative designs of each of the antennas noted so far, and fleshing-out our documentation of recommended/optimal designs in our next report, as we develop/evolve a guide to the practical engineering of these antennas. As always, we appreciate ONR's continuing support for this R&D.

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